Heartwood and sapwood variation in *Acacia melanoxylon* R. Br. trees in Portugal

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Summary

The development of heartwood and sapwood in blackwood (*Acacia melanoxylon* R. Br.) was studied in a total of 20 trees with a 40-cm-diameter class sampled over four stands in northern Portugal at harvest for timber production. Stem discs with 5-cm thickness were taken at different height levels (stem base and 5, 15, 35, 50, 65, 75, 85 and 90 per cent of total height). Cross-sectional area and heartwood area were measured by image analysis. Heartwood represented a substantial part of the trees and within the tree it attained on average 81 per cent of total height, and represented 69, 62, 58 and 44 per cent of the stem cross-sectional area, respectively, at 5, 35, 50 and 65 per cent of total tree height. The heartwood followed closely the stem wood profile both axially and radially. Estimation of heartwood dimensions from external wood diameters (either over or under bark) was possible using a linear model, which had a very high correlation coefficient ($R^2 = 0.97$). The sapwood radial width showed a very small variation within and between trees and maintained a constant value of 31 mm up to ~65 per cent of tree height. No site influence was found for the heartwood development and the between-tree variation was small. The species and the sampled individuals in Portugal showed potential for the diversification of forest production and increasing the industrial supply of a valuable timber hardwood.

Introduction

Acacia melanoxylon R. Br. has its origin in the temperate forests of south-east Australia and Tasmania but it is a versatile and highly adaptive tree species that occurs naturally across a wide range of Australian forest ecosystems (Searle, 2000). This success is in part due to its ability to tolerate wide differences of shade conditions. *Acacia melanoxylon* has been spread all over the world especially because of its ornamental value and the quality of its dark wood.

In Europe, the species is considered as invasive, characterized by vigorous tree or root sprouts and with seed germination stimulated by fire. The issue is especially relevant in southern European countries, i.e. Portugal and Spain, where *A. melanoxylon* strongly resisted against control attempts. In Portugal, *A. melanoxylon* was introduced as an ornamental in the mid-nineteenth century and its expansion occurred in the first half of the twentieth century through national forestation programmes, in which the afforestation projects of coastal dunes included exotics such as *Acacia*,

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Casuarina and *Eucalyptus* (Goes, 1991; Leite *et al.*, 1999). The seed was imported from the region of origin and at that time little was known about the challenges associated with the adaptation of plants and seeds imported from other regions (Silva, 1999). At present, *A. melanoxylon* is found in Portugal associated with maritime pine (*Pinus pinaster* Ait.) and stone pine (*Pinus pinea* L.), in the West Coast or in pure stands or mixed with pines and other hardwoods (i.e. oaks and birch) in the inner part of the country.

Contrary to the value given to the wood of *A. melanoxylon* (blackwood) as a carpentry and cabinet-making wood in its natural region (Jennings *et al.*, 2003), in Europe blackwood has still not found a way into the timber industry.

Blackwood is a medium-density hardwood with basic density ranging between 465 and 671 kg m^{-3}, generally increasing with age, and with a large between-tree variation (Harris and Young, 1988; Clark, 2001). The wood value of *A. melanoxylon* trees is given primarily by their heartwood which shows a rich brown colour and a high natural durability. However, very few references are found in the literature regarding the heartwood characterization in *A. melanoxylon* although between-tree and -site variability of heartwood content and colour was reported for South Africa and both factors proposed as tree selection criteria Harrison (1974, 1975). A recent paper reports on wood density and heartwood proportion in juvenile trees of acacia species (Searle and Owen, 2005).

Heartwood differs from sapwood in chemical composition, density and some physical and technological properties. It varies between and within species and has been related to growth rates, stand and individual tree biometric features, site conditions and genetic control, as reviewed by Hillis (1987), Bamber and Fukazawa (1985) and Taylor *et al.* (2002). Heartwood is impregnated with extractives, which are responsible for the natural durability of this xylem zone and for its usually darker colour. In practice, heartwood content is a stem quality variable that is desirable for timber applications requiring durability and aesthetic value, as is the case with blackwood, but disadvantageous as pulpwood (Pereira *et al.*, 2003).

It is the objective of this paper to study the within-tree heartwood development of *A. melanoxylum* and its between-tree and -site variation as one of the important quality factors to evaluate the timber potential of this species in Portugal. It is a prospective study that looks forward to a high-value use of the existing trees and to a potential forest diversification with this already well-adapted quality hardwood. To do that, 20 trees with commercial timber dimensions from four different sites, located mainly in the north and centre part of Portugal, were harvested and heartwood and sapwood were measured along the stem.

Materials and methods

The study was made on 20 trees of *A. melanoxylon* of unknown seed origin sampled at harvest diameter from four state-owned stands located in northern and central Portugal.

Site 1: Caminha – Mata Nacional do Camarido, 41° 53′ N, 08° 50′ W, altitude 8 m, sandy soils, average annual rainfall 1304 mm, mean temperature 14.3°C.

Site 2: Ponte de Lima – Perímetro Florestal Rebordões Santa Maria, 41° 43′ N, 08° 50′ W, altitude 154 m, granite soils, average annual rainfall 1720 mm, mean temperature 14.0°C.

Site 3: Viseu – Perímetro Florestal do Crasto, 40° 41′ N, 07° 55′ W, altitude 548 m, granite soils, average annual rainfall 1229 mm, mean temperature 13.0°C.

Site 4: Ovar – Perímetro Florestal das Dunas de Ovar, 40° 57′ N, 08° 38′ W, altitude 7 m, sandy soils, average annual rainfall 1152 mm, mean temperature 13.9°C.

Five trees of the same diameter class (40 cm) were harvested per site. Total height, height to crown (up to the first living branch) and overbark diameter at 1.3 m above ground (d.b.h.), as the mean of two crossed diameters, were measured (Table 1).

The trees were bucked and stem discs with 5-cm thickness were taken at different height levels: stem base and 5, 15, 35, 50, 65, 75, 85 and 90 per cent of total height. The discs were allowed to air-dry in naturally ventilated conditions in the laboratory storerooms.

The surface of the stem discs was smoothed by sanding. In all cases, the heartwood was clearly distinguished from the pale coloured

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Table 1: Over-bark diameter at 1.3 m (d.b.h.), number of rings at b.h., bark thickness at 1.3 m, total tree height, crown height and crown level of the harvested trees

	Site 1	Site 2	Site 3	Site 4
d.b.h. (cm)	38.8 (1.7)	38.8 (2.2)	40.3 (2.3)	42.0 (2.5)
Number of rings at b.h.	30	37	38	34
Bark thickness at b.h. (mm)	8.1 (4.0)	9.3 (3.5)	9.0 (4.3)	8.0 (4.0)
Tree height (m)	30.4 (3.6)	33.0 (2.2)	28.7 (2.2)	28.6 (2.9)
Height to live crown base (m)	18.1 (1.9)	12.0 (4.7)	16.8 (4.6)	24.6 (2.8)
Crown level (% of total height)	56.8 (5.5)	41.7 (16.0)	58.2 (10.3)	74.5 (6.5)

Mean of five trees per site and SD in parentheses.

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sapwood by a dark brown colour. The images of the discs were acquired and analysed using the Analysis software (version 3.2, AnalySIS Soft Imaging System GmbH, Munster, Germany). The following areas were measured: total over-bark stem cross-section, bark, total wood, heartwood and sapwood. Average wood and heartwood diameters were calculated considering their areas as circles and sapwood radial width and bark thickness considering a circular cross-section for stem and heartwood (Gominho and Pereira, 2000).

The tree wood volume and the heartwood volume were calculated by sections corresponding to the different height levels of sampling, as conical sections (0–5, 5–15, …, 85–90 per cent) and as a cone (90 per cent top). The sapwood volume was calculated by difference. The height attained by heartwood was calculated for each tree as the intercept of the linear regression of heartwood cross-section areas with height levels. Statistical analysis was performed using the SPSS for windows version 13.0 (LEAD Technologies, Inc., Haddonfield, New Jersey) procedures and the 0.05 level was used in significance tests.

Results

Heartwood development

Heartwood was present in all the trees attaining on average 81 per cent of total height, ranging in individual trees from 67 to 85 per cent of total height. At the 85 per cent height level, only five trees showed heartwood, and at the top level of 90 per cent tree height, no tree presented heartwood. The height attained by the heartwood within the tree showed a tendency to increase with total tree height.

The vertical pattern of heartwood variation was not analysed statistically but appeared similar for all the trees and sites as exemplified in Figure 1 for one tree in each site. The heartwood area in the stem cross-section decreased from the tree base upwards and the heartwood profile followed rather closely the stem wood profile. In the lower part of the stem, the trees showed an irregular shape with an undulating periphery due to the formation of buttresses (Figure 2). This cross-sectional deviation from circularity extended from the base to over 5 per cent of tree height corresponding to approximately the first 2 m of the tree. Butt swelling also occurred.

The vertical heartwood shape accompanied the stem shape and up to 50 per cent of tree height stem taper and heartwood taper were similar at an average 9 mm m^{-1}. For the upper part of the tree, the stem and heartwood tapers increased, especially after the 65 per cent height level, with a significantly higher conicity for the heartwood (Table 2).

The proportion of heartwood in the cross-section remained stable in the lower part of the stem with only a slight decrease until ~50 per cent of the tree height, after which it decreased steadily and sharply in the upper part (Figure 3). On average, heartwood represented 69 per cent at the base and 5 per cent height level, 67, 62 and 58 per cent, respectively, at 15, 35 and 50 per cent of tree height and decreased to 44 and 26 per cent

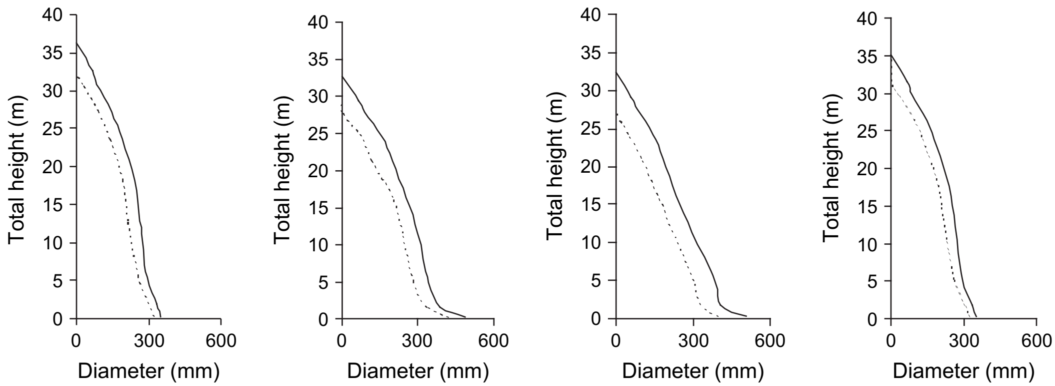

Figure 1. Tree and heartwood profile for one tree in each site (full line represents total diameter, and dashed line represents heartwood diameter).

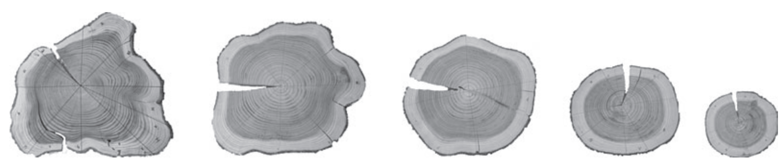

Figure 2. Variation of the stem and heartwood cross-sections for the base, 5, 15, 35 and 50% height levels (from left to right) for one tree of site 3.

Table 2: Variation of tree and heartwood taper values along the stem

Levels of total tree height (%)	Taper, total diameter (mm m^{-1})	Taper, heartwood diameter (mm m^{-1})
5–35	8.9 ± 2.7	9.1 ± 2.7
35–50	9.2 ± 5.7	8.1 ± 4.8
50–65	11.6 ± 4.7	13.6 ± 5.1
65–75	15.7 ± 7.3	19.0 ± 6.8

Mean of 5 trees and SD.

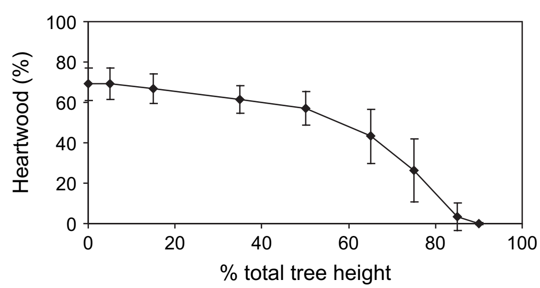

Figure 3. Variation of heartwood content (in % of the stem cross-sectional area) along the tree. Mean of 20 trees and SD as bars.

for the next upper height levels. At the 85 per cent height level, five trees contained heartwood where it represented from 8.2 to 25.2 per cent of the cross-sectional area.

The four sites showed a similar heartwood development pattern, as summarized in Table 3. The Student–Newman–Keuls test (α = 0.05) was applied to all samples at the various height levels and no significant differences between site averages were found for the proportion of heartwood.

Sapwood development

The radial width of sapwood remained practically constant within the tree at an average of 31 mm

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Table 3: Within-tree variation of the heartwood area proportion in the stem cross-section at different height levels for the four stands

Tree total height (%)	Site 1	Site 2	Site 3	Site 4
0	68.9 ± 8.5	71.3 ± 6.4	67.1 ± 10.3	68.9 ± 8.5
5	68.7 ± 8.8	71.1 ± 6.4	68.3 ± 9.1	68.7 ± 8.8
15	67.6 ± 5.7	68.6 ± 7.2	66.5 ± 8.9	65.4 ± 9.0
35	61.9 ± 8.1	61.3 ± 4.3	60.7 ± 8.4	61.9 ± 8.1
50	59.0 ± 9.0	57.0 ± 6.6	52.8 ± 9.2	59.0 ± 9.0
65	49.4 ± 13.4	41.0 ± 11.1	37.6 ± 17.1	45.9 ± 12.6
75	30.8 ± 18.3	26.1 ± 13.5	17.4 ± 13.2	30.8 ± 18.2
85	3.6 ± 4.9	5.0 ± 11.3	0.0 ± 0.0	3.6 ± 4.9

Mean of five trees and SD.

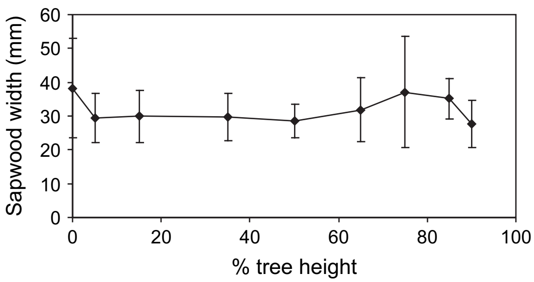

Figure 4. Variation of sapwood radial width along the tree. Mean of 20 trees and SD as bars.

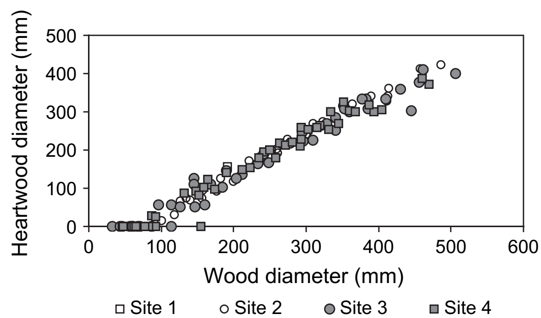

Figure 5. Variation of heartwood diameter with total wood diameter.

in the lower part of the stem until 50 per cent of total tree height, increasing upwards to 35 mm until the 75 per cent height level (Figure 4). At the stem base, sapwood radial width was higher and showed a larger between-tree variability. An increased between-tree variation was also found at the 75 per cent height level, corresponding to a coefficient of variation of the mean of 16.5 per cent.

The Student–Newman–Keuls test ($\alpha = 0.05$) showed that there were no significant differences between sites in relation to sapwood width at the various height levels.

Influence of radial growth on heartwood and sapwood

Figure 5 shows the variation of heartwood diameter with total diameter for all the trees. There is a positive correlation between these two variables in each site and across sites, corresponding to the following linear model, where Dheartwood and Dwood are, respectively, the diameter of heartwood and the wood diameter, expressed in millimetres:

$$\text{Dheartwood} = 0.984\ \text{Dwood} - 59.987 \quad (R^2 = 0.973,\ P < 0.0000).$$

This model estimates that heartwood starts to be formed for tree wood diameters above 61 mm (Dheartwood = 0) and that over this diameter heartwood formation absorbs 98 per cent of the radial wood formation (Dheartwood/Dwood = 0.984).

Estimation of heartwood diameter based on over-bark stem diameter was also possible using the following linear regression, where Dheartwood and Dtotal are, respectively, the diameter of heartwood and the stem over-bark diameter, expressed in millimetres:

$$\text{Dheartwood} = 0.9577\ \text{Dtotal} - 62.136 \quad (R^2 = 0.972,\ P < 0.0000).$$

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The correlation of heartwood diameter with tree size measured at the same height level showed also high values for all stem height positions, as exemplified for the 50 per cent height level in Figure 6. The only exception was the tree bottom where the correlation was less strong although statistically highly significant ($R^2 = 0.78$, $P < 0.0000$).

The heartwood proportion in the stem cross-section increased with the tree radial size until a diameter of ~300 mm and remained constant for larger diameters, as shown on Figure 7.

The sapwood width was independent of the diameter, as shown in Figure 8 for all trees and height levels where heartwood was present.

Heartwood and sapwood volumes

The tree wood volume accumulation along the stem is shown in Figure 9. Volume increases rapidly with tree height in the lower part of the stem, up to ~50 per cent, after which the accumulation of wood volume decreases. From the total tree volume, 82 per cent is accumulated in the first half of the tree stem (Table 4).

Heartwood represented a substantial part of the trees, corresponding on average to 60.9 per cent of the total tree volume. There was no significant influence of site in the tree and heartwood volume variation (Table 4), as given by the Student–Newman–Keuls test (α = 0.05).

Discussion

The sampled trees of *A. melanoxylon* at the end of rotation for timber production, with a class diameter of 40 cm, contained a substantial amount of heartwood (Figure 1). This is an important aspect for the potential timber utilization of blackwood trees since heartwood is

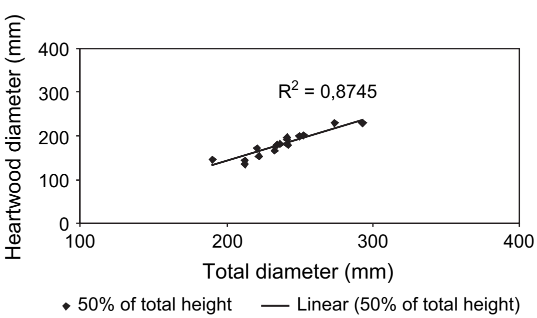

Figure 6. Variation of heartwood diameter with total diameter at 50% of total height, for all the trees.

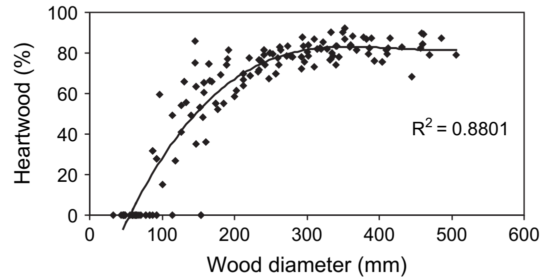

Figure 7. Variation of heartwood proportion in the cross-section with the corresponding total wood diameter.

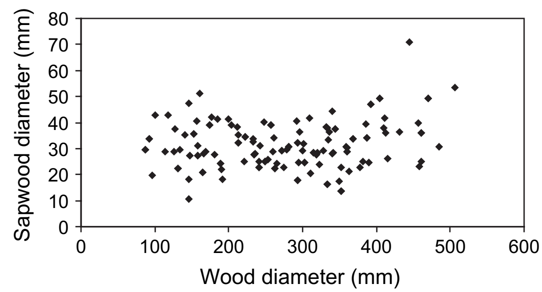

Figure 8. Sapwood width and total wood diameter measured on all cross-sections along tree height where heartwood was present.

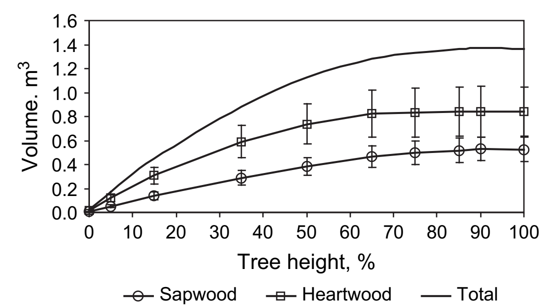

Figure 9. Within-tree development of total, heartwood and sapwood volumes. Mean of 20 trees and SD as bar.

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Table 4: Variation of tree volume and heartwood volume proportion for the trees in the four stands

	Site 1	Site 2	Site 3	Site 4
Total tree volume (m^3)	1.4 ± 0.21	1.3 ± 0.29	1.3 ± 0.27	1.4 ± 0.27
Total heartwood volume (% of total)	61.3 ± 7.80	61.8 ± 5.30	59.8 ± 9.70	60.9 ± 8.90
Tree volume up to 50% of tree height (m^3)	1.1 ± 0.16	1.1 ± 0.23	1.1 ± 0.23	1.2 ± 0.18
Heartwood volume up to 50% of tree height (m^3)	0.7 ± 0.16	0.7 ± 0.19	0.7 ± 0.19	0.8 ± 0.18

Mean of five trees and SD.

considered as one of the most important tree properties to establish the timber value of the stems (Harrison *et al.*, 1974) and the best log prices are usually paid for the dark red-brown-coloured heartwoods with a good diameter and a round shape (Zwaan, 1982). Heartwood represented ~67 per cent of the stem cross-sectional area in the lower part of the tree (Figure 3), attained 81 per cent of the total stem height and in the lower half of the tree heartwood represented 66 per cent of the wood volume (Table 4). These values are much greater than those obtained for the main timber species in Portugal, namely, maritime pine where heartwood represented only 17 per cent of the stem up to 50 per cent of total tree height (Pinto *et al.*, 2004).

Very few references are found in the literature regarding the heartwood content in *A. melanoxylon* and its within-tree development. Harrison (1974, 1975) studied blackwood trees in different locations in South Africa and measured heartwood at several height levels. The average heartwood proportion in the cross-section he found is similar to the values obtained in the present study; i.e. for a wood diameter of 40 cm, heartwood percentage was 83 per cent in the South African trees and ~80 per cent in the Portuguese trees (Figure 7). The curvilinear relationship between under-bark diameter and percentage heartwood (Figure 7) matches closely a similar curve drawn for South African blackwood trees (Harrison, 1974).

Site variation in heartwood was not found in this study and both the axial (Figure 1) and the radial development (Table 2) of heartwood were similar in the four sites. The between-tree variation within each site was also moderate and heartwood proportion at each height level in the lower part of the stem showed coefficients of variation of the mean below 15 per cent (Table 2). The small variation found in heartwood development between trees and sites may be the result of a narrow genetic base for this species in Portugal. Unfortunately, seed lot information is not available.

For South Africa, an effect of environmental conditions was reported and trees from regions with a winter-dormant period showed higher heartwood content, while sites within regions that produce the highest heartwood contents were moist, well drained and with a high organic content (Harrison, 1975). In the case of Portugal, the climatic differences between sites, namely, regarding rainfall and temperature, were not sufficient to induce differences in heartwood formation.

The results obtained concerning heartwood in blackwood are consistent with the general literature available on heartwood development in trees as reviewed, for instance, by Hillis (1987). The heartwood followed closely the stem wood profile, both axially (Figure 1) and circularly in the cross-section (Figure 9). This was especially notorious in the bottom part of the trees, where form was irregular and the heartwood followed the external circumference of the buttresses, allowing for a rather constant sapwood width around the section. An enlargement of heartwood from base to some point in the lower part of the stem was not found in these blackwood trees, contrary to what has been reported for some species or trees, i.e. in maritime pine (Stokes and Berthier, 2000; Pinto *et al.*, 2004; Knapic and Pereira, 2005) or *Pinus sylvestris* L. (Björklund, 1999).

The heartwood diameter was positively correlated with the total diameter (Figure 5) and larger trees had larger heartwoods. Estimation of heartwood dimensions from external wood diameters (either over and under bark) was possible using a linear model with very high correlation factor

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(R^2 = 0.97). This is an aspect of practical importance since the inner heartwood core is the priority of the sawmilling industry. The use of heartwood dimension models makes it possible to estimate its content within a log and therefore its potential value. It was previously shown that the yield of heartwood-sawn products is directly related to the heartwood diameter within the log (Pinto *et al.*, 2005).

Similar heartwood dimensional models have been reported for maritime pine in France, Spain and Portugal (Stokes and Berthier, 2000; Berthier *et al.*, 2001; Ezquerra and Gil, 2001; Pinto *et al.*, 2004; Knapic and Pereira, 2005), and for other pine species such as Scots pine (Björklund, 1999; Morling and Valinger, 1999), *Pinus canariensis* Spreug (Climent *et al.*, 2003) and *Pinus radiata* David Don (Wilkes, 1991).

As regards the relative development of heartwood, measured by its proportion in the cross-section, in relation to tree radial growth (Figure 6), it was found that the heartwood proportion increased steadily with diameter until about a 25-cm diameter, after which the proportion of heartwood remained rather stable and independent of tree size. For wood stem diameters below 10 cm, heartwood was not present.

The literature refers to a positive relation between growth and heartwood, for instance, in maritime pine (Pinto *et al.*, 2004; Knapic and Pereira, 2005), *Eucalyptus globulus* (Gominho and Pereira, 2000, 2005) and *Larix decidua* Miller (Leibundgut, 1983).

Contrary to heartwood, the sapwood radial width showed a very small variation within and between trees with a constant width of 31 mm up to ~50 per cent of tree height (Figure 4). At the base level, the calculated sapwood was larger (38 cm) but this should be an overestimation of the real value, resulting from its method of calculating. In fact, radial dimensions, i.e. heartwood diameter and sapwood width, were calculated assuming a circular form for the stem wood and heartwood. This is clearly not the case due to the existence of buttresses and of an undulating perimeter (Figure 2). When measured directly on a radius, the sapwood width within the tree remains particularly constant, as exemplified clearly for one tree in Figure 2. In addition, no relation between sapwood width and stem wood diameter was found (Figure 8).

These results support the theory that heartwood formation occurs to an extent that regulates the sapwood to a species' specific width in relation with the conducting needs of the crown (Shinozaki *et al.*, 1964). Similar findings were reported for several other species, i.e. maritime pine (Pinto *et al.*, 2004; Knapic and Pereira, 2005), *Pinus banksiana* Lamb. (Yang *et al.*, 1985), *Pinus contorta* Douglas ex Loud. (Yang and Murchison, 1992) and *E. globulus* (Gominho and Pereira, 2005).

The crown effect on the heartwood development is clearly apparent when the location of the living crown base (located in the range of 41.7–74.5 per cent of the tree height, Table 1) is considered. It is at this level that the vertical variation of heartwood diameter and proportion alters its pattern (Tables 2 and 3, Figure 3).

The results obtained showed the high quality of the harvested trees in relation to the heartwood content and therefore to their suitability for sawn products for carpentry, furniture making and other valued applications. This points to the potential exploitation of this species with a silviculture directed towards this type of production. Specifically in Portugal, where most foresters see acacias as an invasive nuisance, a new look at blackwood as a high-quality hardwood could benefit both the industry and the environment. In fact, blackwood grows very well in different parts of the country and it has the characteristics of secondary successions after fire. In relation to heartwood content, the sampled trees showed good characteristics and could be used as genetic material for propagation towards timber production, as advised by Harrison (1975).

Conclusions

Blackwood trees grown in Portugal and harvested at rotation diameter for timber production had a substantial amount of heartwood that occupied most of the stem cross-section and volume of the sawmill-merchantable bole. Their use for quality heartwood timber products showed therefore high economical potential.

No site influence was found for the heartwood development and its between-tree variation was small.

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The species and the sampled individuals in Portugal showed potential for the diversification of forest production and of the industry supply with a valuable timber hardwood.

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